Dark Stars: A New Study of the First Stars in the Universe

Katherine Freese

Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109

E-mail: ktfreese@umich.edu

Peter Bodenheimer

Astronomy Dept., University of California, Santa Cruz, CA 95064

E-mail: peter@ucolick.org

Paolo Gondolo

Physics Dept., University of Utah, Salt Lake City, UT 84112

E-mail: paolo@physics.utah.edu

Douglas Spolyar

Physics Dept., University of California, Santa Cruz, CA 95064

E-mail: dspolyar@physics.ucsc.edu

Abstract. We have proposed that the first phase of stellar evolution in the history of the Universe may be Dark Stars (DS), powered by dark matter heating rather than by nuclear fusion. Weakly Interacting Massive Particles, which may be their own antipartners, collect inside the first stars and annihilate to produce a heat source that can power the stars. A new stellar phase results, a Dark Star, powered by dark matter annihilation as long as there is dark matter fuel, with lifetimes from millions to billions of years. We find that the first stars are very bright ($\sim 10^6 L_\odot$) and cool ($T_{surf} < 10,000$K) during the DS phase, and grow to be very massive (500-1000 times as massive as the Sun). These results differ markedly from the standard picture in the absence of DM heating, in which the maximum mass is about $140 M_\odot$ and the temperatures are much hotter ($T_{surf} > 50,000$K); hence DS should be observationally distinct from standard Pop III stars. Once the dark matter fuel is exhausted, the DS becomes a heavy main sequence star; these stars eventually collapse to form massive black holes that may provide seeds for supermassive black holes observed at early times as well as explanations for recent ARCADE data and for intermediate black holes.

1. Introduction

We have proposed [1] (hereafter Paper I) a new phase of stellar evolution: the first stars to form in the Universe may be Dark Stars, powered by dark matter heating rather than by fusion. Here dark matter, while constituting a negligible fraction of the star's mass, provides the energy source that powers the star. The first stars in the Universe mark the end of the cosmic dark ages, provide the enriched gas required for later stellar generations, contribute to reionization, and may be precursors to black holes that coalesce and power bright early quasars. One of the outstanding problems in astrophysics is to investigate the mass and properties of these first stars. Our results differ in important ways from the standard picture of first stars without DM heating.

Weakly Interacting Massive Particles (WIMPs) are the best motivated dark matter candidates. WIMP annihilation in the early universe provides the right abundance today to explain the dark matter content of our universe. This same annihilation process will take place at later epochs in the universe wherever the dark matter density is sufficiently high to provide rapid annihilation. The first stars to form in the universe are a natural place to look for significant amounts of dark matter annihilation, because they form at the right place and the right time. They form at high redshifts, when the universe was still substantially denser than it is today, and at the high density centers of dark matter haloes.

The first stars form inside dark matter (DM) haloes of $10^6 M_\odot$ (for reviews see e.g. [2, 3, 4, 5]; see also [6, 7].) One star is thought to form inside one such DM halo. The first stars may play an important role in reionization, in seeding supermassive black holes, and in beginning the process of production of heavy elements in later generations of stars.

It was our idea to ask, what is the effect of the DM on these first stars? We studied the behavior of WIMPs in the first stars, and found that they can radically alter the stellar evolution. The annihilation products of the dark matter inside the star can be trapped and deposit enough energy to heat the star and prevent it from further collapse. A new stellar phase results, a Dark Star, powered by DM annihilation as long as there is DM fuel, for millions to billions of years.

1.1. Weakly Interacting Dark Matter

WIMPs are natural dark matter candidates from particle physics. These particles, if present in thermal abundances in the early universe, annihilate with one another so that a predictable number of them remain today. The relic density of these particles is

$$\Omega_\chi h^2 = (3 \times 10^{-26} \text{cm}^3/\text{sec})/\langle \sigma v \rangle_{ann} \tag{1}$$

where the annihilation cross section $\langle \sigma v \rangle_{ann}$ of weak interaction strength automatically gives the right answer, near the WMAP [8] value $\sim 23\%$. This coincidence is known as "the WIMP miracle" and is the reason why WIMPs are taken so seriously as DM candidates. The best WIMP candidate is motivated by Supersymmetry (SUSY): the

lightest neutralino in the Minimal Supersymmetric Standard Model (see the reviews by [9, 10, 11, 12]).

This same annihilation process is also the basis for DM indirect detection searches. The first paper discussing annihilation in stars was [**?**]; the first papers suggesting searches for annihilation products of WIMPs in the Sun were by Silk *et al* [14]; and in the Earth by Freese [15] as well as Krauss, Srednicki and Wilczek [16]. Other studies of WIMPs in today's stars (less powerful than in the first stars) include [17, 18, 19, 20, 21, 22]. This article reviews the study of WIMP annihilation as a heat source for the first stars.

As our canonical parameter values, we take $m_\chi = 100\text{GeV}$ for the WIMP mass and $\langle \sigma v \rangle_{ann} = 3 \times 10^{-26} \text{cm}^3/\text{sec}$ for the annihilation cross section but consider a variety of masses and cross sections.

2. Three Criteria for Dark Matter Heating

WIMP annihilation produces energy at a rate per unit volume

$$Q_{\text{ann}} = \langle \sigma v \rangle_{ann} \rho_\chi^2 / m_\chi \simeq 10^{-29} \frac{\text{erg}}{\text{cm}^3/\text{s}} \; \frac{\langle \sigma v \rangle}{(3 \times 10^{-26}\text{cm}^3/\text{s})} \left(\frac{n_h}{\text{cm}^{-3}} \right)^{1.6} \left(\frac{100\text{GeV}}{m_\chi} \right) (2)$$

where ρ_χ is the DM energy density inside the star and n_h is the stellar hydrogen density. Paper I [1] outlined the three key ingredients for Dark Stars: 1) high dark matter densities, 2) the annihilation products get stuck inside the star, and 3) DM heating wins over other cooling or heating mechanisms. These same ingredients are required throughout the evolution of the dark stars, whether during the protostellar phase or during the main sequence phase.

First criterion: High Dark Matter density inside the star. One can see from Eq.(2) that the DM annihilation rate scales as WIMP density squared, because two WIMPs must find each other to annihilate. Thus the annihilation is significant wherever the density is high enough. Dark matter annihilation is a powerful energy source in these first stars (and not in today's stars) because the dark matter density is high. First, DM densities in the early universe were higher by $(1+z)^3$. Second, the first stars form exactly in the centers of DM haloes where the densities are high (as opposed to today's stars which are scattered throughout the disk of the galaxy rather than at the Galactic Center). We assume for our standard case that the DM density inside the $10^6 M_\odot$ DM halo initially has an NFW (Navarro, Frenk & White [23]) profile for both DM and gas, with substantial DM in the center of the halo (we note that we obtain qualitatively the same result for cored haloes). Third, a further DM enhancement takes place in the center of the halo: as the protostar forms, it deepens the potential well at the center and pulls in more DM as well. We have computed this enhancement in several ways [1] as discussed in the next paragraph. Fourth, the original DS is only $\sim 1 M_\odot$; then it accretes more baryons as well as more DM up to almost 1000 $M_\odot$, in the process increasing the DM density inside the star. Fifth, at later stages, we also

consider possible further enhancement due to capture of DM into the star (discussed below).

Enhanced DM density due to adiabatic contraction: Paper I recognized a key effect that increases the DM density: adiabatic contraction (AC). As the gas falls into the star, the DM is gravitationally pulled along with it. Given the initial NFW profile, we follow its response to the changing baryonic gravitational potential as the gas condenses. Paper I used a simple Blumenthal method [24], which assumes circular particle orbits to obtain estimates of the density. Our original DM profile matched that obtained numerically in [6] with $\rho_\chi \propto r^{-1.9}$, for both their earliest and latest profiles; see also [25] for a discussion. Subsequently we performed an exact calculation [27] using the Young method [26] which includes radial orbits, and confirmed our original results (within a factor of two). Thus we feel confident that we may use the simple Blumenthal method in our work. We found

$$\rho_\chi \sim 5(\text{GeV}/\text{cm}^3)(n_h/\text{cm}^{-3})^{0.81}, \tag{3}$$

where n_h is the gas density. For example, due to this contraction, at a hydrogen density of $10^{13}/\text{cm}^3$, the DM density is 10^{11} GeV/cm^3. Without adiabatic contraction, DM heating in the first stars would be so small as to be irrelevant.

Second Criterion: Dark Matter Annihilation Products get stuck inside the star. In the early stages of Pop III star formation, when the gas density is low, most of the annihilation energy is radiated away [28]. However, as the gas collapses and its density increases, a substantial fraction f_Q of the annihilation energy is deposited into the gas, heating it up at a rate $f_Q Q_{\text{ann}}$ per unit volume. While neutrinos escape from the cloud without depositing an appreciable amount of energy, electrons and photons can transmit energy to the core. We have computed estimates of this fraction f_Q as the core becomes more dense. Once $n \sim 10^{11}\text{cm}^{-3}$ (for 100 GeV WIMPs), e$^-$ and photons are trapped and we can take $f_Q \sim 2/3$.

Third Criterion: DM Heating is the dominant heating/cooling mechanism in the star. We find that, for WIMP mass $m_\chi = 100\text{GeV}$ (1 GeV), a crucial transition takes place when the gas density reaches $n > 10^{13}\text{cm}^{-3}$ ($n > 10^9\text{cm}^{-3}$). Above this density, DM heating dominates over all relevant cooling mechanisms, the most important being H$_2$ cooling [29].

Figure 1 shows evolutionary tracks of the protostar in the temperature-density phase plane with DM heating included (Yoshida et al. [30]), for two DM particle masses (10 GeV and 100 GeV). Moving to the right on this plot is equivalent to moving forward in time. Once the black dots are reached, DM heating dominates over cooling inside the star, and the Dark Star phase begins. The protostellar core is prevented from cooling and collapsing further. The size of the core at this point is ~ 17 A.U. and its mass is $\sim 0.6 M_\odot$ for 100 GeV mass WIMPs. A new type of object is created, a Dark Star supported by DM annihilation rather than fusion.
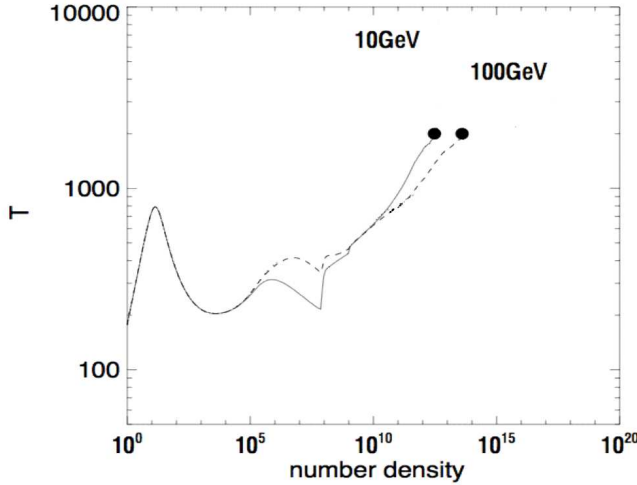
Figure 1. Temperature (in degrees K) as a function of hydrogen density (in cm^{-3}) for the first protostars, with DM annihilation included, for two different DM particle masses (10 GeV and 100 GeV). Moving to the right in the figure corresponds to moving forward in time. Once the "dots" are reached, DM annihilation wins over H$_2$ cooling, and a Dark Star is created.

3. Building up the Mass

This point is the beginning of the life of the dark star, a DM powered star which lasts until the DM fuel runs out. We have found the stellar structure of the dark stars (hereafter DS) [31]. After forming with the properties described in the previous paragraph, the DS accrete mass from the surrounding medium. In our paper we build up the DS mass as it grows from $\sim 1 M_\odot$ to $\sim 1000 M_\odot$. As further gas accretes onto the DS, more DM is pulled along with it into the star. At each step in the accretion process, we compute the resultant DM profile in the dark star by using the Blumenthal prescription for adiabatic contraction.The DM density profile is calculated at each iteration of the stellar structure, so that the DM luminosity can be determined.

We allow surrounding matter from the original baryonic core to accrete onto the DS,with three different assumptions for the mass accretion: (i) $3 \times 10^{-3} M_\odot$/yr, (ii) the variable rate from Tan & McKee [32] and (iii) the variable rate from O'Shea & Norman [33]. The Tan/McKee rate decreases from 1.5×10^{-2} M$_\odot$/yr at a DS mass of 3 M$_\odot$ to 1.5×10^{-3} M$_\odot$/yr at 1000 M$_\odot$. The O'Shea/Norman rate decreases from 3×10^{-2} M$_\odot$/yr at a DS mass of 3 M$_\odot$ to 3.3×10^{-4} M$_\odot$/yr at 1000 M$_\odot$. As the mass increases, the DS radius adjusts until the DM heating matches its radiated luminosity. We find polytropic solutions for dark stars in hydrostatic and thermal equilibrium. We build up the DS by accreting $1 M_\odot$ at a time, always finding equilibrium solutions. We find that initially the DS are in convective equilibrium; from $(100 - 400) M_\odot$ there is a transition to radiative; and heavier DS are radiative. As the DS grows, it pulls in more DM, which then annihilates. We continue this process until the DM fuel runs out at $M_{DS} \sim 800 M_\odot$

(for 100 GeV WIMPs).

We have performed a complete study of building up the dark star mass and finding the stellar structure at each step in mass accretion. In addition to the heating due to DM annihilation, we included additional heat sources due to gravitational potential energy and fusion in the later stages of accretion, as the DM begins to run out and the star contracts and heats up.

Thus the energy supply for the star changes with time and comes from four major sources:

$$L_{\text{tot}} = L_{DM} + L_{\text{grav}} + L_{\text{nuc}} + L_{\text{cap}}, \tag{4}$$

where the ingredients are the DM luminosity L_{DM}; gravitational contraction L_{grav} (as the DM begins to run out); fusion luminosity L_{nuc} (once the star has contracted enough to reach high temperatures for fusion); and the contribution L_{cap} to the luminosity due to captured DM (discussed below). The general thermal equilibrium condition is then that the stellar luminosity L_* match the heat supply,

$$L_* = L_{\text{tot}}. \tag{5}$$

FIgure 2 shows the different contributions to the luminosity as a function of time for the 100 GeV case using the Tan/McKee accretion rate. We include feedback mechanisms which can prevent further accretion. Once the stellar surface becomes hot enough, when the DM is running out, the radiation can prevent accretion.

Figure 3 shows the stellar structure for the case of constant accretion rate and assuming a convective star (n=1.5); more accurate results will be found in our upcoming paper. One can see "the power of darkness:" although the DM constitutes a tiny fraction ($< 10^{-3}$) of the mass of the DS, it can power the star. The reason is that WIMP annihilation is a very efficient power source: 2/3 of the initial energy of the WIMPs is converted into useful energy for the star, whereas only 1% of baryonic rest mass energy is useful to a star via fusion.

4. Later stages: Capture

The dark stars will last as long as the DM fuel inside them persists. The original DM inside the stars runs out in about a million years. However, as discussed in the next paragraph, the DM may be replenished by capture, so that the DS can live indefinitely due to DS annihilation. Capture only becomes important once the DS is already large (hundreds of solar masses), and only with the additional particle physics ingredient of a significant WIMP/nucleon elastic scattering cross section at or near the current experimental bounds.

The new source of DM in the first stars is capture of DM particles from the ambient medium. Any DM particle that passes through the DS has some probability of interacting with a nucleus in the star and being captured. The new particle physics ingredient required here is a significant scattering cross section between the WIMPs and nuclei. Whereas the annihilation cross section is fixed by the relic density, the
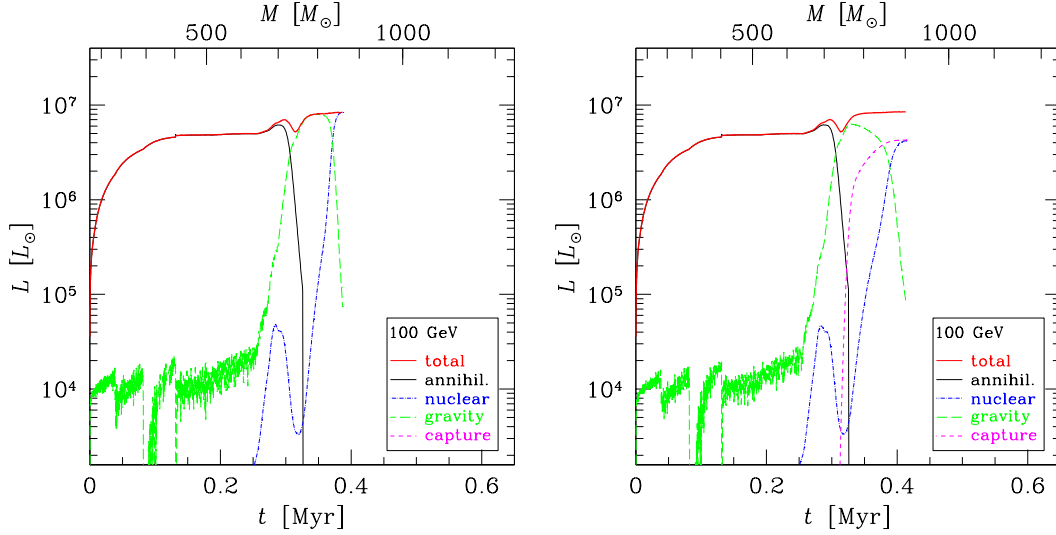
Figure 2. Luminosity evolution for the 100 GeV case as a function of time (*lower scale*) and stellar mass (*upper scale*). The solid (red) top curve is the total luminosity. The lower curves give the partial contributions of different sources of energy powering the star a) (*upper frame*) without capture, and b) (*lower frame*) with 'minimal' capture. In both frames, the total luminosity is initially dominated by DM annihilation (the total and annihilation curves are indistinguishable until about 0.3 Myr after the beginning of the simulation); then gravity dominates, followed by nuclear fusion. In the lower frame, capture becomes important at late times.
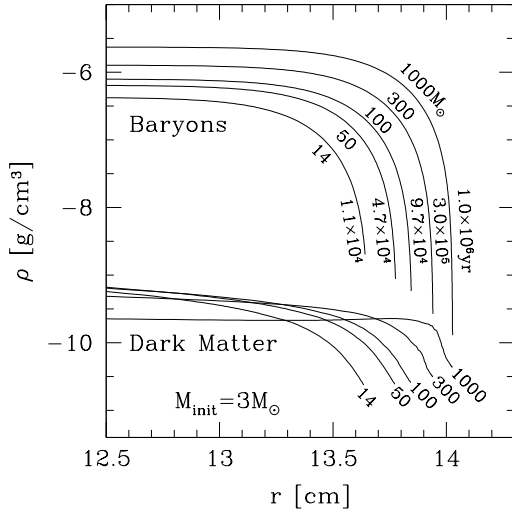

Figure 3. Evolution of a dark star (n=1.5) as mass is accreted onto the initial protostellar core of 3 $M_\odot$; this figure assumes a constant accretion rate $\dot{M} = 3 \times 10^{-3} M_\odot/\mathrm{yr}$. The set of upper (lower) curves correspond to the baryonic (DM) density profile at different masses and times. Note that DM constitutes $< 10^{-3}$ of the mass of the DS.

scattering cross section is a somewhat free parameter, set only by bounds from direct detection experiments. Two simultaneous papers [37, 38] found the same basic idea:

the DM luminosity from captured WIMPs can be larger than fusion for the DS. Two uncertainties exist here: the scattering cross section, and the amount of DM in the ambient medium to capture from. DS studies following the original papers that include capture have assumed (i) the maximal scattering cross sections allowed by experimental bounds and (ii) ambient DM densities that are never depleted. With these assumptions, DS evolution models with DM heating after the onset of fusion have now been studied in several papers [39, 40, 41]. The two original papers on capture in Pop III stars, as well as these additional papers, would all apply to later generations of stars (vs. the very first ones), as the stellar masses on the Zero Age Main Sequence (ZAMS) were taken to be $\sim 100 M_\odot$.

We suspect that the DS will eventually leave their high density homes in the centers of DM haloes, especially once mergers of haloes with other objects takes place, and then the DM fuel will run out. The star will eventually be powered by fusion. Whenever it again encounters a high DM density region, the DS can capture more DM and be born again.

In our work, we have considered two separate cases: 1) 'no capture': the case where ambient density and/or scattering cross section are simply not high enough for capture to matter and (ii) 'minimal capture": the case where the stellar luminosity (on the ZAMS) has equal contributions from DM heating and from fusion.

If the capture rate were much higher, say two or more orders of magnitude higher than the minimal value considered here, the star could stay DM powered and sufficiently cool such that baryons can in principle continue to accrete onto the star indefinitely, or at least until the star is disrupted. This latter case will be explored in a future paper where it will be shown that the dark star could easily end up with a mass on the order of several tens of thousands of solar masses and a lifetime of least tens of millions of years.

5. Results and Predictions

While DM powers the dark stars, they are cool (surface temperatures less than 10,000K) and bright ($10^6 L_\odot$). These properties are very different from standard Pop III stars, which are $\sim 140 M_\odot$ [32] and have surface temperatures exceeding 30,000K. One can thus hope to find DS and differentiate them from standard Pop III stars, e.g. in JWST.

Once the DM fuel runs out inside the DS, the star contracts until it reaches 10^8K and fusion sets in. Our final result [31] in all cases is very large first stars; e.g., for 100 GeV WIMPs, the first stars have $M_{DS} = 800 M_\odot$. The implication is that main-sequence stars of Pop. III are very massive. Regardless of uncertain parameters such as the DM particle mass, the accretion rate, and scattering, DS are cool, massive, puffy and extended. The final masses lie in the range 500–1000 $M_\odot$, very weakly dependent on particle masses, which were taken to vary over a factor of 10^4.

One may ask how long the dark stars live. If there is no capture, they live until the DM they are able to pull in via adiabatic contraction runs out; the numerical results

show lifetimes in the range 3×10^5 to 5×10^5 yr. If there is capture, they can continue to exist as long as they reside in a medium with a high enough density of dark matter to provide their entire energy by scattering, capture, and annihilation.

Once the stars are on the Main Sequence, powered by fusion, they will not last very long before collapsing to form black holes. DS would make plausible precursors of the $10^9 M_\odot$ black holes observed at $z = 6$ [42, 43]; of Intermediate Mass Black Holes; of black holes at the centers of galaxies; and of the black holes recently inferred as an explanation of the extragalactic radio excess seen by the ARCADE experiment [44]. However, see Alvarez et al. (2008) who present caveats regarding the growth of early black holes. The final fate of our stars once they reach the MS is uncertain; it is possible that they could become supernovae [45], leaving behind perhaps half their mass as black holes. In this case the presumed very bright supernova could possibly be observable, and the resultant black holes could still be important. In addition, the black hole remnants from DS could play a role in high-redshift gamma ray bursts thought to take place due to accretion onto early black holes (we thank G. Kanbach for making us aware of this possibility).

Standard Pop III stars are thought to be $\sim (100 - 200) M_\odot$, whereas DS lead to far more massive MS stars. Heger & Woosley [34] showed that for $140 M_\odot < M < 260 M_\odot$, pair instability supernovae lead to odd-even effects in the nuclei produced; such element abundances have not been observed. Other constraints on DS will arise from cosmological considerations. A first study of their effects (and those of the resultant MS stars) on reionization have been done by Schleicher et al [46], and further work in this direction is warranted.

6. Conclusion

95% of the mass in galaxies and clusters of galaxies is in the form of an unknown type of dark matter. One of the key properties of WIMP candidates is its annihilation cross section, yielding the proper relic density today. As a consequence of this annihilation, the first stars in the universe may provide another avenue to test the DM hypothesis. These stars may be powered by DM annihilation, and one can look for them in upcoming telescopes. It is an exciting prospect to discover a new type of star powered by the dark matter in the universe.

In short, the first stars to form in the universe may be Dark Stars powered by DM heating rather than by fusion. Our work indicates that they may be very large ($800 M_\odot$ for 100 GeV mass WIMPs). Once DS are found, one can use them as a tool to study the properties of WIMPs.

We also briefly mention a separate work [47], in which we studied a different possible dark matter candidate: we studied the effect of primordial black holes on the first stars. We found that these small black holes, again adiabatically contracted into the first stars, fall to the center of the star by dynamical friction. There they form a single large black hole which can eat the entire star and accrete from the surrounding medium. Again we

have a mechanism for forming $> 1000 M_\odot$ black holes at early times, which may explain or serve as seeds for the intermediate mass or large black holes found in many places in the universe.

7. Acknowledgments

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